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**A TECHNICAL DEMONSTRATION OF
A MAP BASED LOGISTICS
PLANNING TOOL**

by

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September, 1997

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The post Cold War is characterized by a wide range of possible military missions, from full scale war to peace keeping missions and by great uncertainty about when and where military response will be required. Military planning systems (for example, logistics, counter-logistics, protection of infrastructure, and infrastructure restoration) must be flexible enough to allow rapid response to situations whose details can not be anticipated. These advanced systems must be able to coordinate resources (maps, overlays, networks, algorithms, models, people) over a distributed network of heterogeneous computers and systems.

This thesis develops a prototype system to demonstrate some of these capabilities. The system loads maps, data files, and algorithms from a computer network and has algorithms to determine optimal ways to disrupt, restore, or protect logistics networks. The planning tool displays the data as an overlay on a map and is user interactive for modification and sensitivity analysis. The system is developed using the Java programming language and thus can be executed without change in a variety of computer environments.

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A TECHNICAL DEMONSTRATION OF A MAP BASED LOGISTICS PLANNING TOOL

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Submitted in partial fulfillment
of the requirements for the degree of

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ABSTRACT

The post Cold War is characterized by a wide range of possible military missions, from full scale war to peace keeping missions and by great uncertainty about when and where military response will be required. Military planning systems (for example, logistics, counter-logistics, protection of infrastructure, and infrastructure restoration) must be flexible enough to allow rapid response to situations whose details can not be anticipated. These advanced systems must be able to coordinate resources (maps, overlays, networks, algorithms, models, people) over a distributed network of heterogeneous computers and systems.

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EXECUTIVE SUMMARY

The post Cold War is characterized by a wide range of possible military missions, from full scale war to peace keeping missions and by great uncertainty about when and where military response will be required. Military planning systems must be flexible enough to allow rapid response to situations whose details can not be anticipated. They must contain enough functionality to be useful yet generic enough to be tailored to specific situations. The planning systems must be able to distribute pertinent information to multiple sites across great distances into different computing environments. Current planning systems are limited in their ability to do this. The technology exists today to meet the above requirements.

This thesis designed and developed a prototype logistics planning tool that demonstrates these capabilities. The planning system can load maps and build overlays to represent a logistics infrastructure in a geographical region. The planning sytem uses an algorithm to determine the optimal ways to disrupt, restore, or protect logistics networks. A different approach to system design, component based design, was used. The advantage of component based design is that the program can be modified without changing the overall functionality of the system. Unlike previous systems that were designed for a predetermined situation, this system can be tailored to the requirements of specific situations. Instead of trying to make the situation conform to the planning tool, the planning tool can be tailored to the situation.

The planning tool is written in a new language called Java [Ref. 11]. There are many

advantages to using Java. The language incorporates established standards and protocols which make accessing and distributing information over information networks, such as the internet, easy. Another advantage to Java is that it is not platform specific. The same compiled code can run on many different computing environments without having to be recompiled. In addition, components can be added to the planning tool without recompiling which allows for modification of the system without losing any functionality.

This thesis demonstrates a generic planning tool based on component design that can run in a variety of computing environments and be tailored to unforeseen situations. Capabilities can be added to the tool with few lines of code. The system is interactive; the data can be modified and reanalyzed while the program is running. Unlike monolithic legacy systems, which are cumbersome and costly to change, a tool of this design can be quite easily modified to situations whose details can not be anticipated. This thesis is a part of a larger project to develop dynamic planning systems based on a component architecture. The source code can be obtained on request from Professor Gordon Bradley (bradley@nps.navy.mil), Department of Operations Research, Naval Postgraduate School, Monterey, CA 93940-5000.

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I. INTRODUCTION

The center of gravity of any military operation can be justifiably argued to be the logistics tail. The term "military operation" encompasses a wide variety of meanings, from full scale major regional contingencies to humanitarian assistance and nation building. Since a well planned logistics operation is fundamental to the success of any of these, it is essential to understand both the enemy's logistics as well as one's own. The success of any operation is dependent on logistics and all logistics infrastructures are susceptible to the same vulnerabilities. A thorough knowledge of all aspects of logistics from interdiction of the logistics infrastructure, to infrastructure defense, to restoration and repair of damaged networks is essential for logistics planners to provide useful and effective information to decision makers.

This thesis lays the foundation for the development of tools to assist the logistics planner in assessing the logistical situation and to support the decision making process. It is a technical demonstration of capabilities available today that can be used in flexible logistics planning applications that may include unpredictable circumstances. This research has developed a user interactive, map based planning tool that represents an infrastructure network in both a geographic and abstract representation and solves for the maximum flow from any source(s) to any destination(s). In addition, it also identifies and visually highlights the vulnerable links in the network for rapid assimilation of information. It operates over an information network, such as the internet, to access and download maps and data files; it constructs overlays and interacts with heterogeneous computing environments.

A. BACKGROUND

The very nature of logistics lends itself to being represented by network graphs. The flow of essential items from source to customer can be represented as a flow network. Fitting easily into the network flow models are infrastructure networks such as potable water, petroleum and natural gas.

The concept of modeling infrastructure networks and attempting to interdict them is not a new one. During the Vietnam war, network interdiction was conducted on supply lines into South Vietnam. More recently in the war on drugs, supply line interdiction was attempted on pre-cursor chemicals used in the production of drugs.

In addition to interdiction, infrastructure defense has gained importance on the national level. The President's Commission on Critical Infrastructure Protection (PCCIP) was created by executive order in July 1996 and is charged with assessing the risk to systems in eight areas such as telecommunications, electric power systems, gas and oil production and its storage and transportation, and water supply systems [Ref. 10]. Private industries such as electric power and telecommunications companies use advanced solvers to determine how best to effect repairs on damaged networks.

A decision aid of this nature can be used in military operations other than war (MOOTW). It can assess the host nation capabilities and provide insight as to the logistics requirements that aiding forces need to supply to meet the intent of a MOOTW operation.

Studies have shown that past interdiction efforts produced little effect on the flow of logistics. One of the shortcomings of the interdictions conducted in Vietnam was that battle damage assessment was poor and the ability of the enemy to repair or modify the network was difficult to model [Ref. 12]. Likewise, studies on the interdiction of pre-cursor chemicals in the war on drugs have had little effect on reducing the flow of drugs [Ref. 13]. The interdiction of transportation routes of pre-cursor chemicals through jungle paths in the Columbian mountains was near impossible. The limited success of network models in interdiction against smart adversaries adept in modifying and repairing their networks does not reflect on their value in other logistics situations.

With the utilization of a planning tool that allows for quick modification of the network combined with the computing speed of personal computers, past shortcomings can be avoided by continually monitoring and reassessing the current situation and conducting sensitivity analysis on the set of possible decisions. A planning tool that can be used to assess infrastructure networks, identify vulnerable areas, and quickly disseminate information, can be used in developing plans to deny an enemy of war essential items, in developing defenses for our own infrastructure, and in planning repair and restitution to damaged networks.

1. Current Situation

Following the collapse of the former Soviet Union and the end to the Cold War military planners face significant uncertainty. The Chairman of the Joint Chiefs has desribed the threat: "The U.S. must prepare to face a wider range of threats, emerging unpredictably, employing varying combinations of technology, and challenging us at varying levels of intensity." Joint Vision 2010 [Ref. 1] At the height of the Cold War, the military threat was well defined, tactics and doctrine were developed and mathematical models and simulations were used to train leaders and planners how to respond and with what assets. The level of uncertainty as to where the military will operate, with whom, and overall mission and goals has increased dramatically. The range of military operations in the 1990's has been from a Major Regional Contingency (the Gulf War), to Minor Regional Conflict (Bosnia), to Humanitarian Assistance (Haiti), to continual counter-drug operations.

The Joint Staff, Director of Space Warfare (N6), Admiral Arthur Cebrowski, and the Commander in Chief Pacific Fleet (CINCPACFLT), Admiral Archie Clemins, are exploring new technologies to be implemented today to keep in step with the corporate sector [Ref. 1,2,3]. There appears to be a shift in paradigm from traditional warfare; the Chief of Naval Operations, Admiral Jay Johnson, describes this new approach as a "fundamental shift from what we call platform-centric warfare to something we call network-centric warfare" [Ref. 2] where all levels of command and control are connected via an information network. If network centric warfare is going to be a part of how warfare is conducted, then we must use the technology available and design planning systems that exploit the nature of information networks. By utilizing current off-the-shelf technology and incorporating it into the planning tools of the near future, the military can expand its capabilities and reduce its requirements for new equipment.

Planning tools of the future should be capable of exchanging information on computer networks (such as the internet), execute without change in different computing environments, and be easily modified to handle unanticipated requirements. These tools need to be inexpensive in both acquisition of new systems and in maintenance and modification. In addition, the next generation of software tools will need to be designed such that the elapsed time between identification of a needed capability and its implementation should be in terms of hours and not years. This requires a paradigm shift from monolithic legacy systems designed for very specific circumstances that are difficult to modify, to a design of systems composed of components that can be quickly modified to deal with unanticipated situations. Component design increases the robustness of any system in that the complete list of capabilities required need not be identified before the software is developed. As capabilities are identified, they are easily added into the tool. This leads to generic applications where the capabilities are defined by the user and the situation at hand and not by the planning tool. The technology exists today to meet all of the above capabilities and requirements.

B. COORDINATION WITH MULTIPLE ORGANIZATIONS

Today's operations cross not only service lines, but agency and national lines. For many of the MOOTW operations, the military will be working jointly with more than one military service and working in combination with other government agencies and non-government and private organizations as well as with international governments and agencies. In many cases, organizations such as the Peace Corps and the American Red Cross are well established in underdeveloped nations with all of the required information for planning. The planning tool must be able to import information quickly and easily from the systems that these organizations have. It cannot be assumed that the computers and operating systems used by these organizations will be equivalent to that of the U.S. military. Therefore, the planning system must allow for information sharing with these other participants and must also be able to sensor what each organization or agency receives.

Today's planners have to be ready for and quickly respond to *unanticipated* situations in all regions of the world, cooperating with unknown forces and agencies. They will need the ability to assess and reassess the situation as it changes. "Warfighting requirements will vary based on type of military operation, forces involved, combat environment, and other factors. Each mission requires somewhat different capabilities due to variations in the type of operation, commander's intent, and concept of operation."[Ref. 4] The Chairman of the Joint Chiefs of Staff agree that requirements will change from mission to mission, and as such, the capabilities of the planning tools must change as well.

C. NEEDED CAPABILITIES

The Department of Defense as well as individual services have conducted research into what future systems should be capable of. The "Joint Vision 2010" from the Joint Staff [1], the Air Force Scientific Advisory Board study "New World Vistas" [Ref. 5], CINCPACFLT's "Information Technology for the 21st Century " (IT-21) [Ref. 3], and CNO-N6's "Network Centric Warfare: A Revolution in Military Affairs"[Ref. 2], provide guidance on the requirements for future systems.

Capabilities are defined as components of the tool that provide a function or perform a process that enhances the total amount of information provided to the user. The planning tool must have the ability to display the current situation simultaneously and at various and multiple sites. A system that can do this is said to be a distributed system. The current situation needs to be displayed on computer terminals in a command center in the United States as well as at the regional command post and/or on a field computer on site at the center of the activity. In order to do this, the system must be platform independent, that is, able to run on a range of different machines including work stations, personal computers, as well as hand held pocket computers. There must be built into the system a command and control function that allows for one operator to allocate degrees of access and levels of interaction on the information. Control is then established over who receives the information and which users are allowed to modify the existing information. This leads to a user interface which allows for modification of data by authorized users as the situation changes.

The tool must be able to read data from databases, files, or, if none exist, manually from a keyboard. It must also be able to quickly display a map of the region in question and allow for overlays on the map. Because the underlying premise for designing such a tool is that the situations encountered are unanticipated, it is imperative that system be designed so that other capabilities can be added with quickness and ease. Once the data is entered and the infrastructure network is displayed there must be a means by which to modify it and do analysis on the network. The operations that the military confronts today are as dynamic as they are unpredictable, therefore, it is essential to have a tool that can modify and analyze a continually changing situation.

The planning tool must incorporate the ability to save the work done. It is important to preserve data for historical and archival purposes as well as post conflict analysis and "lessons learned " reports. It also essential to save work in progress for back up reasons and to conduct sensitivity analysis without corrupting the source data.

As stated earlier, the situations faced today are unanticipated, unpredictable, and dynamic. A key element in any decision making process is sensitivity analysis on possible courses of action. Therefore, the above capabilities are both necessary and sufficient to provide pertinent and useful information to the decision maker.

D. GOAL

The goal of this thesis is to develop a map based planning tool that meets many of the requirements for future systems as stated in references 1, 2, and 3. The technology exists today to meet the goals and to incorporate all of the needed capabilities into a generic planning tool. With established standards and protocols, and a new approach to the architecture, coordination between all participants need not be a problem. A system based on a "components" design can be modified quickly and easily to meet the dynamic nature military operations. New or modified data from any user connected to the information network can provide near real time information on the current situation to all locations globally. Information is gathered, entered, and analyzed and rapidly disseminated to decision makers which is fundamental in developing an appropriate course of action. This is true for any situation be it peace keeping, disaster relief, or full scale combat. This thesis describes the design and implementation of a baseline structure of a planning tool generic enough to cover all of these situations yet simple enough to use with very little training.

This thesis demonstrates that it is possible to meet the requirement for future planning tools that can be used for unanticipated situations and provide answers to unforeseen questions. In addition, such planning systems can be implemented and supported at a minimal cost. This is demonstrated by designing and building a specific map based logistics planning tool that can be utilized for military operations occurring in any region of the world.

II. PLANNING TOOL DESIGN

The challenge in the design of a planning tool is that given an immediate unanticipated situation, available assets should be utilized to allow for a decision maker to gather information, analyze the situation and act. Furthermore, when the information is modified as the situation changes, the planning tool must allow the decision maker to reassess and develop follow-on courses of action (COA's).

The system must be portable, extensible, and robust with the ability to be distributed on a computer network. It must be portable in that it can be used on any machine regardless of the underlying operating system, extensible so that capabilities may be added quickly and easily without a major rewriting of the code, and robust so that the tool can be utilized in situations that are yet unforeseen. Extensibility demands that the design be simple; without simplicity, adding additional capabilities would become a complex and time consuming process.

A. BASELINE STRUCTURE AND DESIGN

The product of this thesis is designed and implemented in the programming language Java version 1.02 from Sun Microsystems. The tool is able to load maps and existing infrastructure networks in the form of data and display them in two forms, abstract and geographic. Figures 1 and 2 are examples of abstract and geographic representations. The planner can analyze the network and solve for the maximum flow from any node or group of nodes to any other node or group of nodes and display the results on both representations

of the network. The system is user interactive. A user is able to "click" on any node or arc on either representation and view the characteristics and modify them as necessary. Any change on one representation is reflected on the other. If the data is modified, the user is able to immediately re-analyze the network.

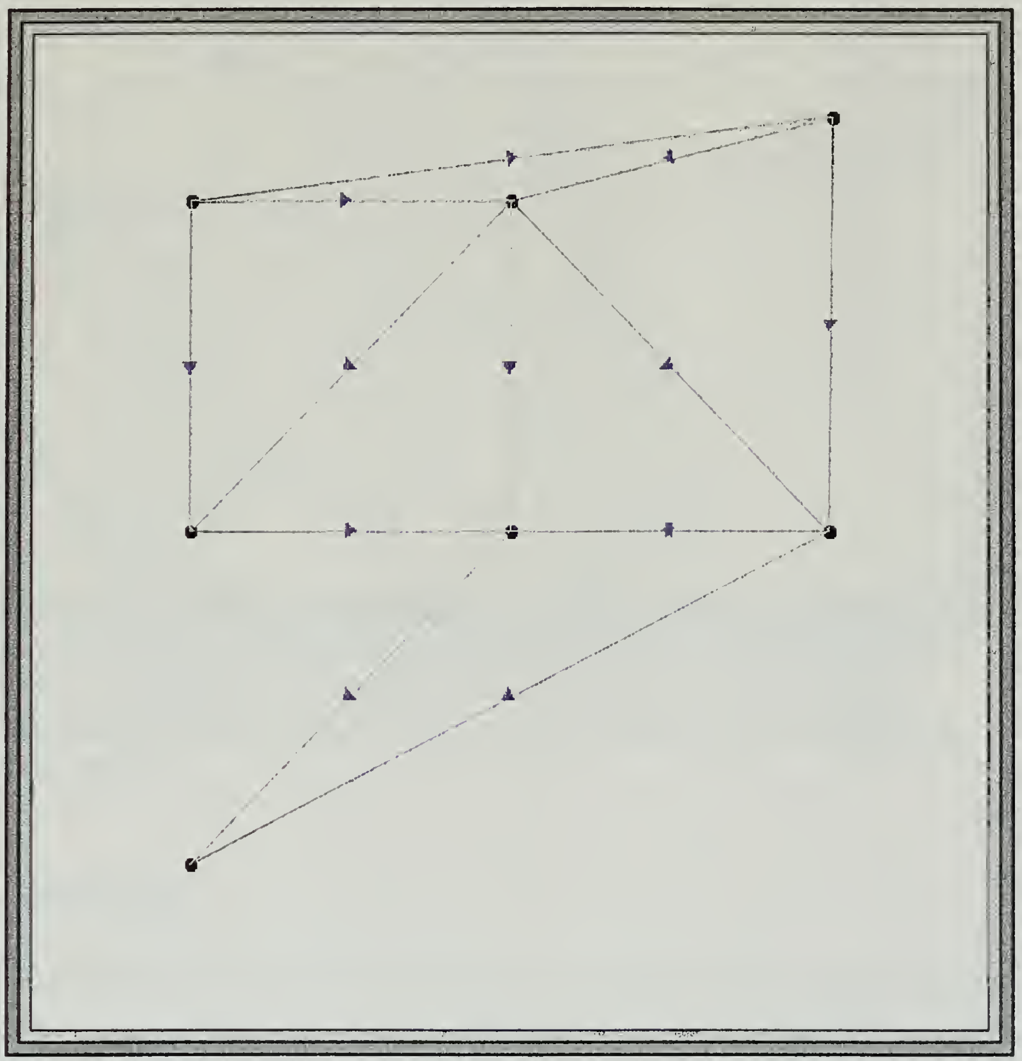

Figure 1 : The abstract view illustrates the relative relationship between the nodes and arcs. It shows which nodes are connected and the direction of flow. The user can click and drag the nodes to clarify the presentation.

Figure 2: The geographic display rigidly places the nodes at their assigned latitude and longitude. The nodes can only be moved by changing their assigned latitudes and longitudes. This view provides network orientation to the "real world".

B. PORTABLE

The portability issue has been a very frustrating obstacle for past programming languages. "For the past decade computer hardware has been providing approximately 25% more power per dollar per year. Computer vendors are doubling the speed of processors every 18 months or so. The problem with this fast paced of hardware development, is the

increasingly difficult problem of writing software that can take advantage of the hardware's capabilities. To make matters worse a program written today for a certain chip isn't guaranteed to run tomorrow."[Ref. 6] For a program to be truly portable it should be compiled only once and thereafter it should run on any system at any time. Languages such as C++ and Fortran need specific operating systems in order for the compiled code to work. One of the many characteristics of Java is its portability which makes it an ideal choice of programming language for projects of this nature.

The map based planning tool was written and compiled on a personal computer and has been tested on various operating system to ensure portability. The program has successfully run on a personal computer with Windows 95, and a Sun SPARC workstation. There are some minor requirements to support portability such as having access to the Java "virtual machine", which can be loaded onto many systems quite easily with minimal storage space. Sun Microsystems claims to be able to run a Java program on something as small as cellular phone, thus broadening the range of portability.

C. EXTENSIBLE

To achieve the requirement of extensibility requires a shift from procedural style programming with rigidly couple subroutines and procedures, to object oriented programming designed with classes and methods. Object oriented programs consists of several pieces called classes. The idea is to have many small classes that perform a singular type or set of tasks. In addition, the major components of the system must be designed so that it is easy to add additional functionality to the system without changing the existing

capabilities.

In addition, the classes do not need to be stored on the machine running the program. The only requirement is that a path be established to where the classes reside, either on the same machine or on another machine on the network. For a Java program to use a class, the main program is required only to know what parameters must be passed and what, if anything, is returned. Adding a link to a class can be as simple as one or two lines of code, achieving extensibility quickly, and easily. Java is dubbed as the "language of the internet". The language allows for retrieving items from uniform resource locators (URL) sites on the internet. With a few lines of code, a Java program can access a URL site and retrieve various types of files, including classes, which can then be used directly in the program without stopping the program or recompiling. By reflecting on this issue, it is easy to see the power that extensibility brings to this style of program. All of the classes and data files need not be on the computer being used, the system requires just a link to the sites where they are. This is an extremely useful capability for small field computers used in combat or in remote locations with a satellite connection to a base computer. By accessing assets only as needed from the network, the portable computer can have the capabilities of a much larger computer.

D. SIMPLE DESIGN

The structure of the program has to be kept simple to allow for the easy modification of the planning tool. The most common foreseen modification is adding capabilities not yet contained within the program. For instance, the program contains one basic algorithm for

solving maximum flows and identifying the set of arcs in a minimum cutset (Appendix A). One modification that may be added is an algorithm that optimizes interdiction of a given network. There are several algorithms written in other languages that can be converted into Java which can then be added to the menu of solvers. Adding a solver to the menu requires only four or five lines of code.

By keeping the design simple, capabilities can be extended by adding classes directly onto the machine in use or by adding a link to where they reside. This quickly enhances the planning tool capabilities. Figure 3 illustrates the simple, component design. The user interface in this example is linked to classes that contain maps, data, solutions, and algorithms. The map class is linked to a URL site which provides the maps to the program and the algorithm class is illustrating that various solvers are linked to the algorithm class

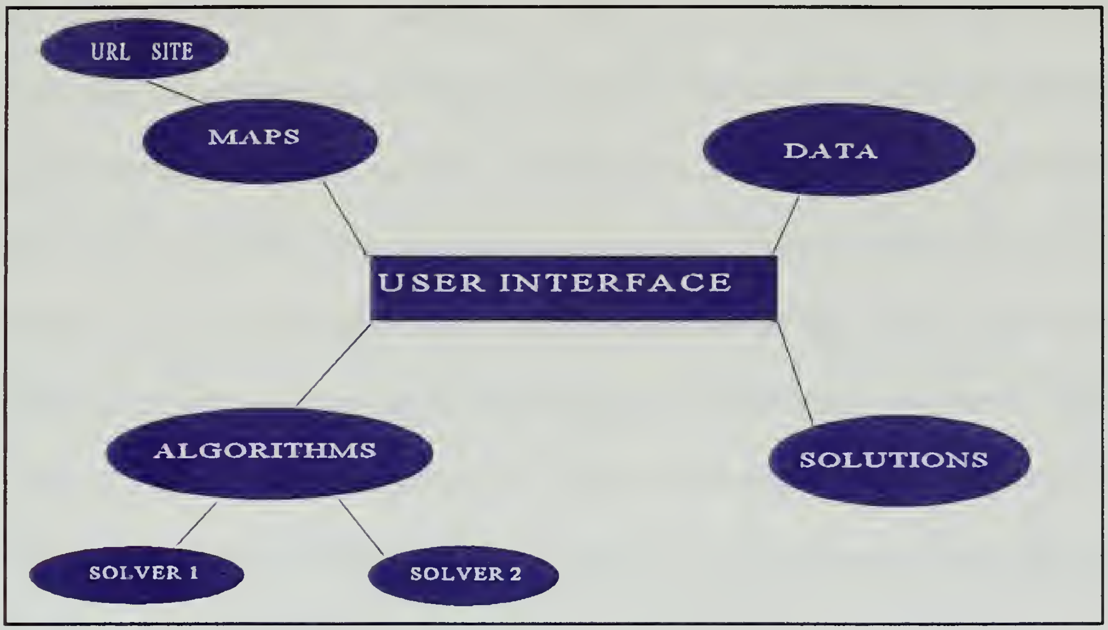

Figure 3: The pictorial illustration depicts the links to the user interface. These loosely coupled links allow the user to utilize only those elements necessary to the task at hand. The design enables additional links to be added easily.

but not necessarily contained on the user's machine. The component design idea supports adding capabilities by simply calling the class needed, directly from the user's machine or over the network. Classes may call other classes which may, in turn, call others ad infinitum. The point is not necessarily accessing capabilities from a remote site, many "rigid" systems already do this, but accessing capabilities that were not originally planned for and adding them with four or five lines of code without having to recompile the entire program and without changing the functionality of the existing code. A simple design with this capability is extremely robust especially when all possible required capabilities of the planning tool can not be foreseen.

E. CAPABILITIES

The capabilities incorporated into the program meet the minimum required to achieve the goals stated above. The technical demonstration does not utilize all of the capabilities provided by Java. However, it demonstrates those capabilities that allow the desired tasks defined by the goals of the system to be performed. The first and foremost capability is that the model is extensible. Because it is extensible and capabilities can be added quickly and easily, any limitation of capabilities is only a limitation when it is identified as such. Once identified, it is easily added by creating a link to the desired capability. If the capability required does not yet exist or its residence is unknown, then the requirement can be coded and added to the program. The only difficulty in this approach is the coding which is dependent on what is desired. However, once coded, adding the capability is quite easily done.

Using Java delivers some of the requirements of the systems such as portability and platform neutral architecture. Portability exemplifies the robustness of this type of tool because the environment in which it is run is not limited to a specific machine or operating system type. The uncertainty of where, when, and with whom the tool will be used dictates that this be the case. Having software capable of providing the answers needed has little value if it is unable to run on the machines available. The portability capability also eliminates the time consuming process of recompiling every time the system is moved to a different machine or environment. The planning tool is written in a language that is capable of being written and compiled only once yet it can be run in many environments.

The idea of a generic planning tool coupled with the above capabilities allows for a number of system capabilities. The planning tool, as it currently exists, is capable of the following:

- Infrastructure Analysis Through Exploitation of Network Characteristics:
  First and foremost, an infrastructure network can be loaded into the tool and displayed. Any structure that lends itself to be represented as a series of nodes and arcs can be read into the program. These may range from water distribution pipelines to communications networks. A current limitation is that the solver incorporated works only with network flows that behave linearly.

- Load and Build Overlays:
  The program is capable of not only loading maps, but is also able to load and build overlays on them increasing the amount and value of the information displayed. The abstract view alone does not provide enough information for a decision maker to quickly react.

- Geographic Plot:
  The addition of a geographic plot, a map with infrastructure overlay, orients the users and stimulates solutions to the problem. The interactiveness between the two views enhances the robustness of the tool since the user is no longer limited

to just one view. This capability increases the speed of modifying the network, keeping the representation near real time.

The tool analyzes the network by solving for maximum flow through the network, providing the value of that flow and highlighting the cutset. The results can be stored which provides reproduceabilty which is important for historical analysis. It is the analysis of the infrastructure network that makes the tool useful and is an equally important capability. Taken one at a time, these capabilities are not unique, it is the combined result of all of the capabilities in the design of the tool which make it stand out.

To recap the capabilities, the program can load networks and maps, display the networks abstractly and as an overlay on a map. It can analyze the network in the form of solving a maximum flow and displaying the resultant cutset and maximum flow value. The network can be modified quickly as the situation changes. The data and analytical results can be stored and loaded back into the tool for further analysis or historical recreation of events. The planning tool can provide valuable information today and capabilities can be added without overhauling the entire system to provide the needed yet unknown capabilities of the future.

F. FEATURES

The current features incorporated into the tool allow for quick and easy display of information as well as modification. This section will identify features and will show examples through a series of figures that are screen captures of the program being run with a fictitious network in a series of figures and text. The network displayed has seven nodes

[illegible]

and thirteen arcs and is geographically located in Monterey, California. The dual display of both the geographic and abstract representation are shown in Figure 4.

Figure 4: Screen capture of both the abstract and geographic display.

The abstract representation introduces the idea of an automatic graph layout tool. Unlike the geographic representation where the locations of the nodes are fixed by latitude and longitude, the node locations on the abstract view have to be assigned by the program. Graph layout tools are the mechanisms used to assign node positions. There are graph layout tools available commercially however, these can be quite expensive. Developing a

graph layout tool is a significant task and beyond the scope of this thesis. For these reasons, the map based planning tool includes a graph layout tool that was written in Java by a student at the Max Plank Institute in Germany [Ref. 7]. The code was made available for use by its author and was down loaded from the internet and incorporated into the map based planning tool.

There are three possible layouts of the abstract displays available, random, circular, and grid, Figures 5, 6, and 7, the default being grid. In addition to the preprogrammed abstract displays, the user can modify any abstract display by moving individual nodes to

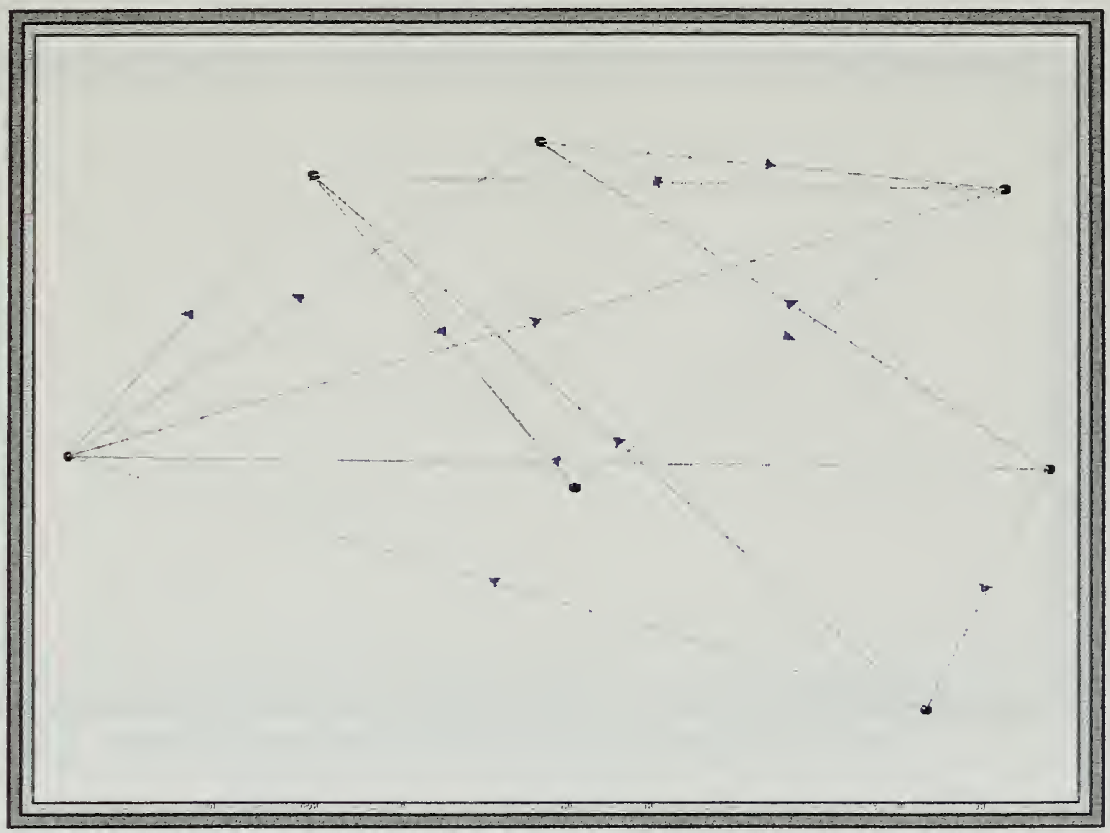

Figure 5: Automatic graph layout with random placement of the nodes

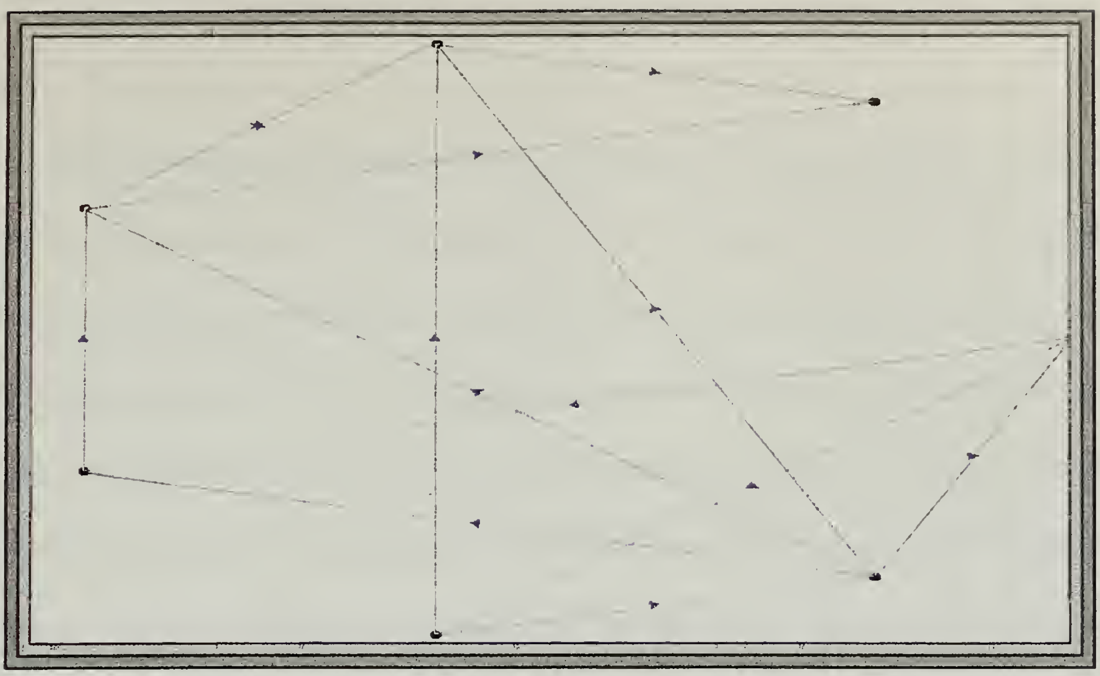

Figure 6: Automatic graph layout with the nodes positioned in a circular fashion.

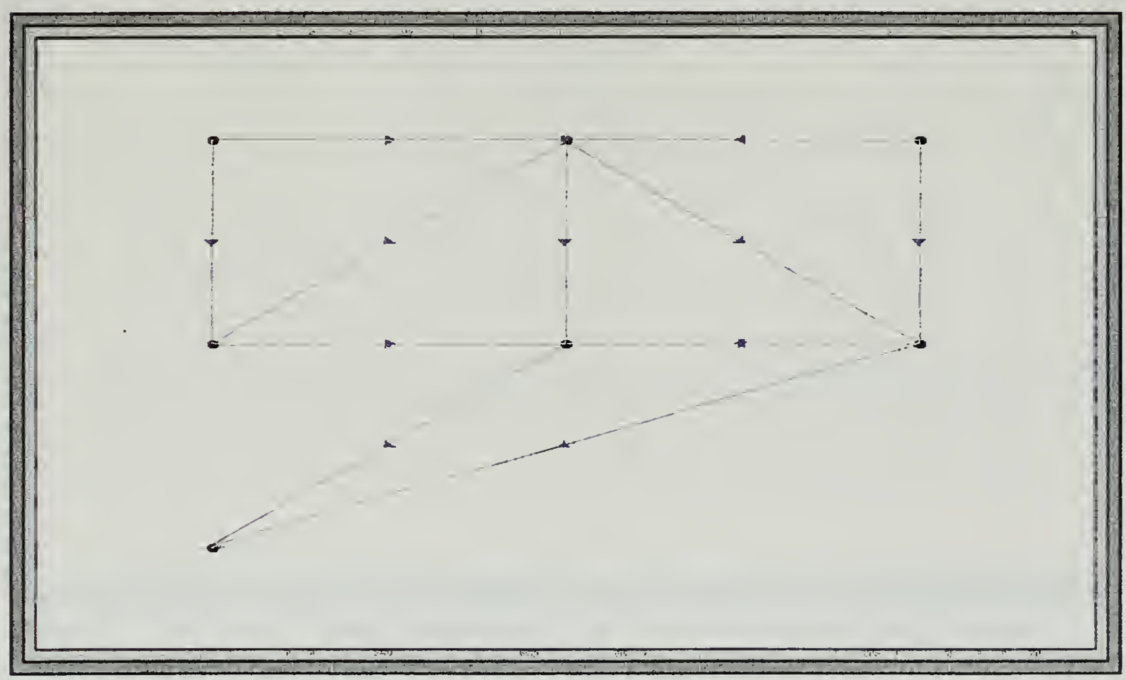

Figure 7: Automatic graph layout with the nodes a placed in grid format.

any location on the display. The arrowheads indicating the direction of flow can be moved along the length of the arcs. This enables the user to minimize clutter on displays that contain many nodes and arcs. This is extremely useful on dense graphs because arcs and flow pointers may be hidden due to being drawn over one another. The arcs automatically adjust maintaining integrity between the node being moved and the stationary node. Furthermore, the arrowhead pointing in the direction of flow automatically adjusts its geometry to remain pointing in the proper direction. Figure 8 demonstrates these features.

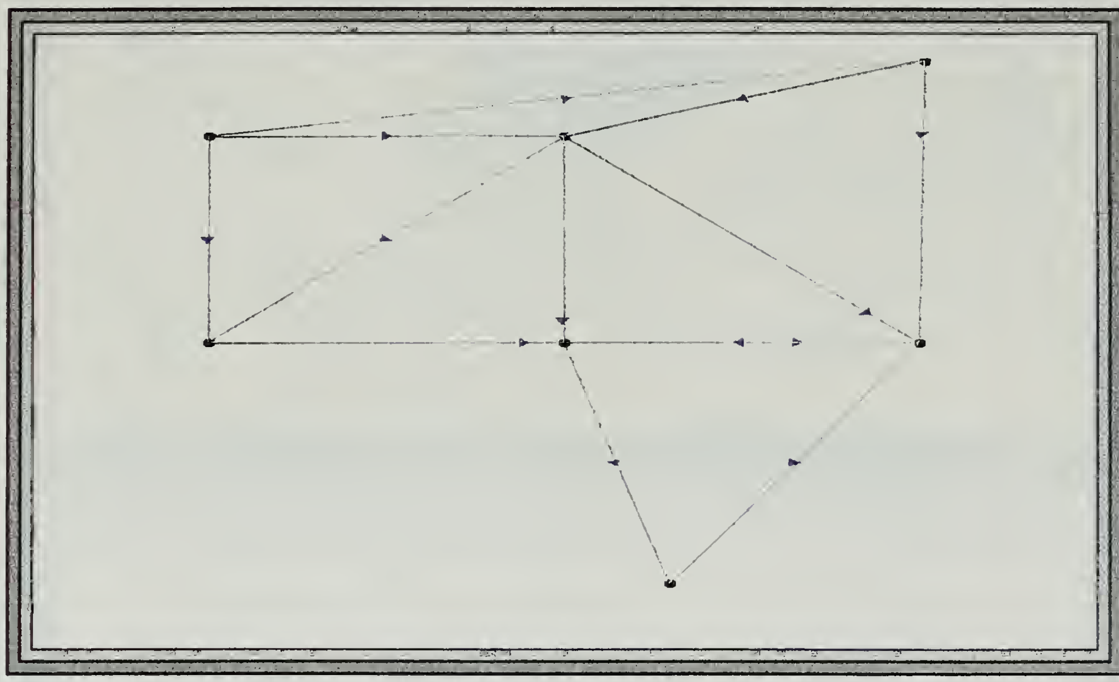

Figure 8: The above display demonstrates the ability to move individual nodes. Figure 7 was modified by moving Node 3 which reveals an arc from node 1 to node 3 that was hidden in the original grid display. Node 7 from figure 7 was also moved. Flow pointers are initially placed at the midpoint of the arc. Five pointers above have been repositioned.

The displays do not show the attributes of the arcs and nodes. It is important for the user to be able to access this information for a given node or arc. This can be done as shown in Figure 9. If the network is dense and there is a considerable amount of overlay, the user can highlight specific arcs by clicking on the arrowhead of the arc causing the arc color to change to red. If the arc's arrowhead is not conveniently located, it can be moved along the arc by clicking on the arrowhead and dragging it along the arc. The two displays are linked by a common set of arcs and nodes, therefore, when an arc on one display is highlighted, the same arc on the other display is also highlighted as shown in Figure 9.

Figure 9: Dual display showing highlighted arcs and arrowheads repositioned. The attribute dialog box displays the attributes of the highlighted arc. The data can be changed by editing the dialog box.

During the analysis of a scenario, there may be a need to enter a new arc or node to the network. This task, though tedious for a large number of additions, is quite simply done on either display as depicted in Figure10. The procedure for adding nodes and arcs requires multiple steps, however, since the two displays share a common set of nodes and arcs, it need only be performed on only one of the displays. It is essential that the new node be assigned a name different from any other node and a latitude and longitude provided for placement on the geographic display. New nodes created on the geographic display will automatically be assigned the latitude and longitude of the location where it was placed.

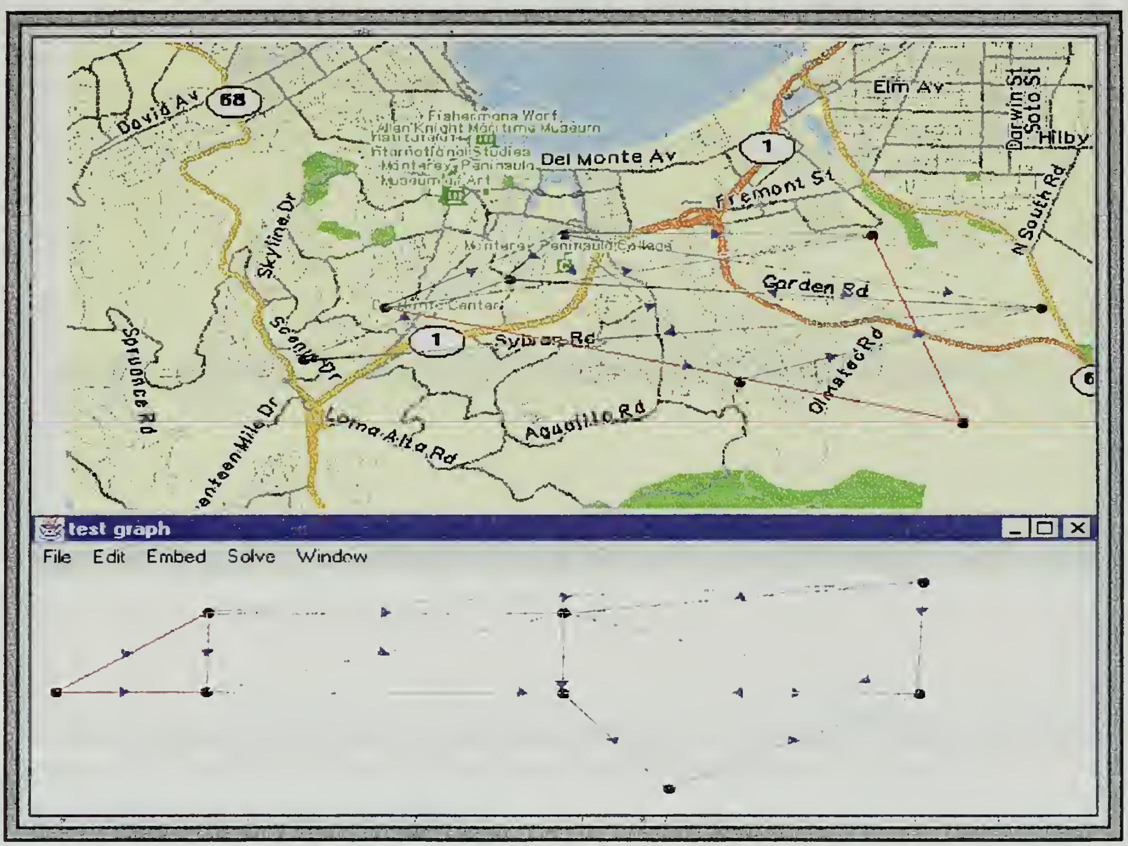

Figure 10: A new node and two new arcs added to figure (9). The new arcs connect the new node to nodes 1 and 4 and are identified on both displays by the highlighted arcs.

Equally important is the ability to delete arcs and nodes. Figure 11 is the previous figure after the deletion of a single arc, from node 3 to node 2, and a single node, node 1. Deleting a node automatically deletes all arcs emanating from or terminating at it, as depicted in Figure 11. These features allow for quick modification of a changing network. Once modified, new analysis can be conducted on the network.

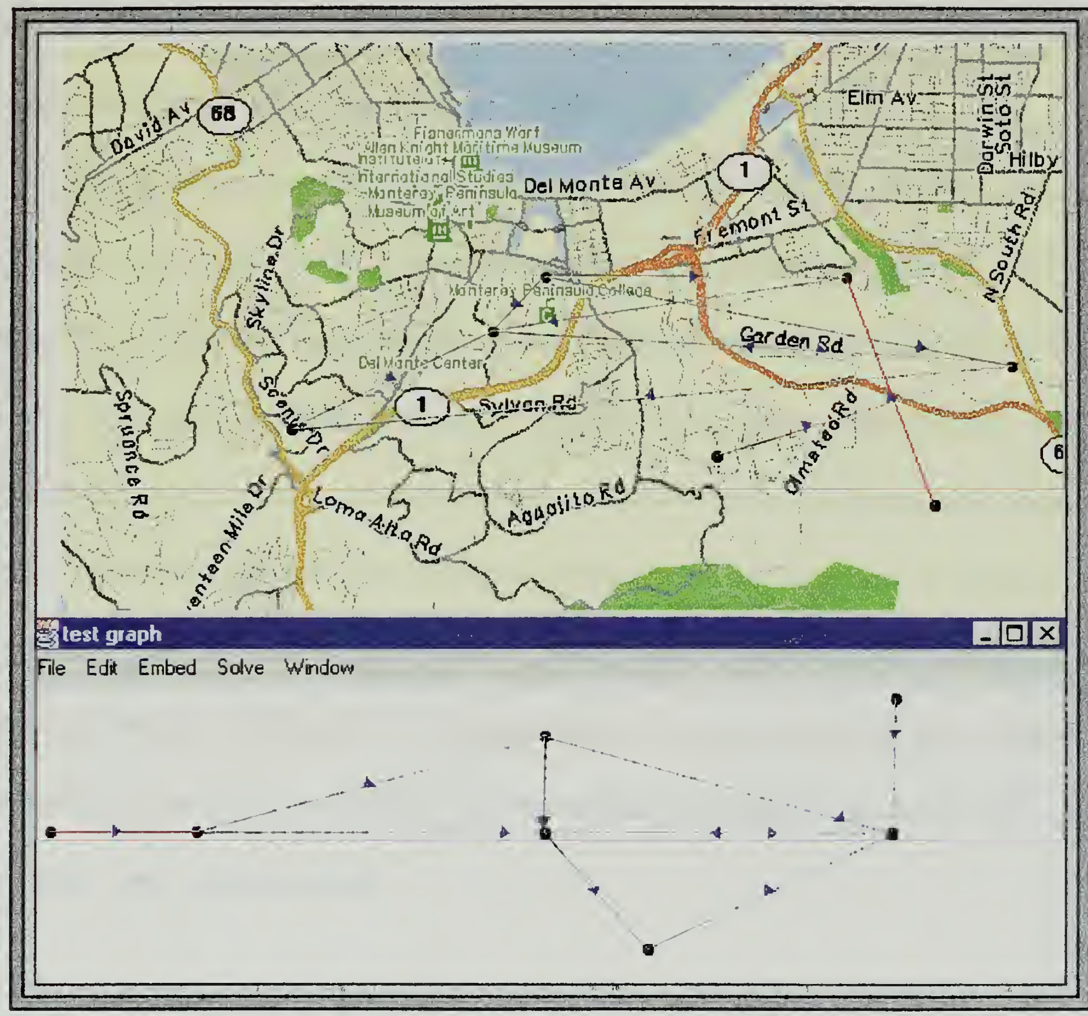

Figure 11: Display after an arc has been deleted and after a node (and its associated arcs) has been deleted.

The abstract display can be resized and reshaped to fit anywhere on the screen. Both the abstract and geographic display can be repositioned on the screen allowing the user to organize the screen in a way that displays the information most effectively. The map can be disposed of and then redrawn at the discretion of the user without losing the integrity of the information displayed. This feature is valuable when the abstract display is cluttered and resizing the abstract display is necessary to aid in repositioning the nodes for clarity. The geographic display provides orientation to the user allowing for a decision maker to assess the situation at a glance and then move on to other issues.

Analysis is conducted from the menu bar of the abstract display as shown in Figure 12. Under the menu item *solver*, is the option *maxflow*. When the user invokes the *maxflow* option, a text box appears requesting the source node or nodes and the sink node or nodes. The solver computes the maxflow value and highlights the arcs of the cutset on both displays as well as the source node(s) and sink node(s). All source nodes are green, sink nodes are yellow. With the abstract view arranged properly, the combination of abstract and geographic views show both the cutset and verifies that the cutset in fact disconnects the source and the sink. In Figure 12 it is not obvious at first glance that the cutset displayed is disconnecting the source and sink yet the abstract display leaves no doubt that the source and sink are disconnected.

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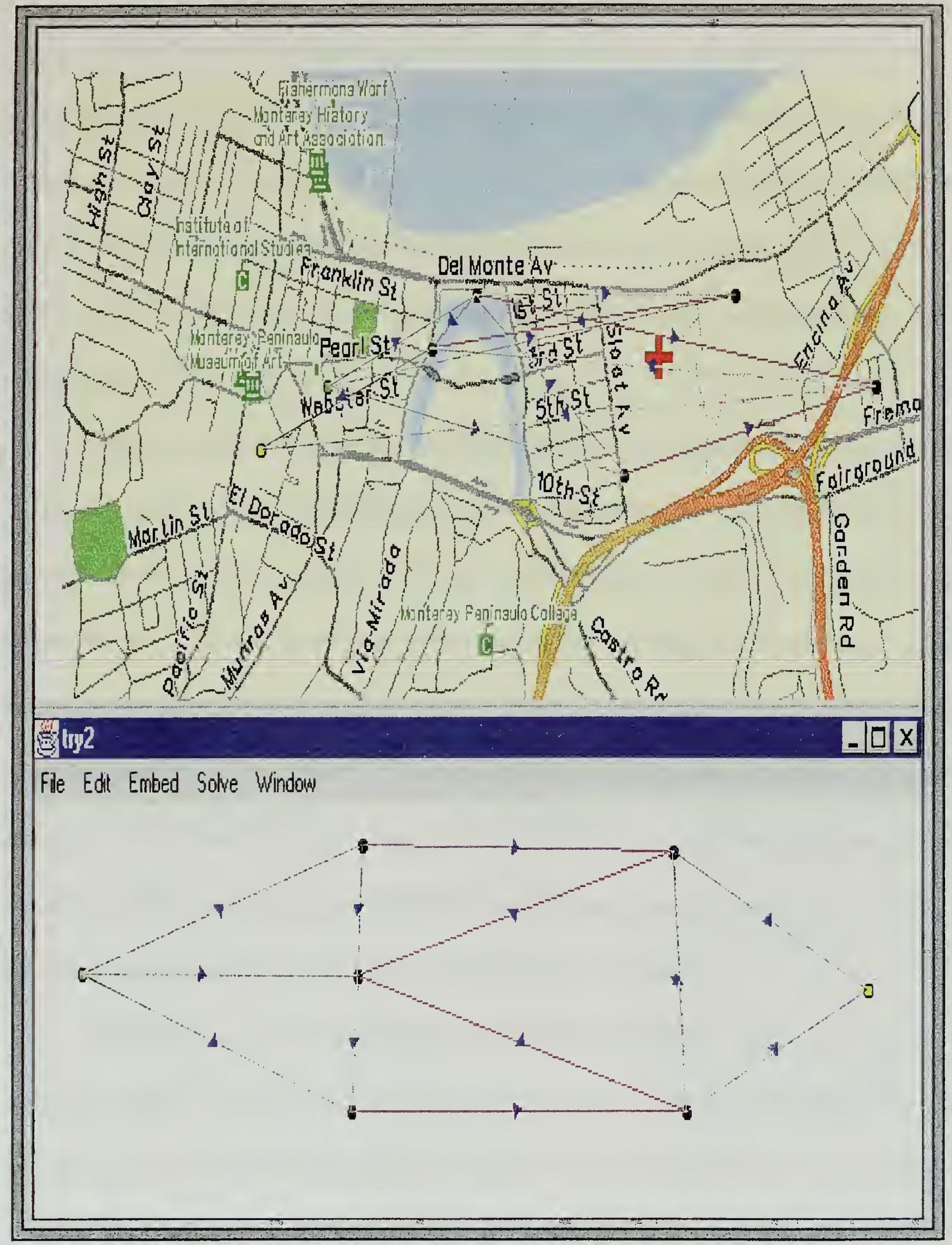

Figure 12: In the geographic display, the cutset is not apparent or obvious however, there is no doubt that in the abstract view the cutset disconnects the source and sink nodes.

G. LIMITATIONS

As a technical demonstration, this thesis incorporates an approach to achieving each goal previously mentioned. The thesis provides only a sample of the type of capabilities a planning tool of this nature can contain. With only a sample of capabilities demonstrated, the true potential of the design may not be fully realized by the reader. This is a limitation that is forced by the scope of the thesis and not of the design or implementation of the planning tool.

There are limitations specific to the capabilities of the demonstrated planning tool. A maximum flow algorithm was used which is limited in the amount of information it can provide. The algorithm works only with directed networks and the flow being modeled must behave linearly. This limits analysis to systems such as pipelines and roadways or unitless values that are assumed to be linear in nature. There are many other optimization problems other than maximum flow that can be posed and may be of greater significance to military analysts. The implementation of the algorithm is such that it produces *a* minimum cutset. Multiple optimal cutsets may exist and the algorithm constructs only one. It does not provide any insight into whether there is more than one cutset.

The addition of arcs and nodes can become tedious and there is no device for catching mistakes. Incorrect data entered into the program will provide misleading results that appear to be correct. The geographic display window will allow the user to resize the view of the map however, the scale of the map is fixed which means that the latitudes and longitudes will adjust to a resized window where as the map will not. In other words, if the map window size is changed, the position of the nodes will change but the map will not, therefore it no longer depicts the true geographic position of the network. There is no "zoom" quality to the map, the representation that is initially displayed is the only scale and size available. If the map is inadvertently resized, the user can close the map window and then redraw the map and the proper depiction will be shown.

There are indeed many other approaches that can be used to develop a system that achieves the same goals. Furthermore, many other capabilities can be added to the planning tool to enhance the model. Limitations identified here are limitations to the current capabilities incorporated in the model and are not limitations on the design or structure of the system.

III. ILLUSTRATIVE EXAMPLES

The previous chapters provide the background and specify requirements for the design of a generic planning tool. They also describe the capabilities and limitations of the system as well as showing some of the features of a map based planning tool. The following sections of this chapter describe possible scenarios where the map based planning tool could be used to provide pertinent and useful information to a decision maker.

A. SCENARIO: HUMANITARIAN ASSISTANCE

An underdeveloped, third world nation has just experienced a massive earthquake which has destroyed much of the nation's fresh water distribution system. The nation has requested assistance from the United Nations. The United States has taken the lead and deployed a U.S. Army Corps Support Group (CSG) with an Engineering Battalion to the scene. The CSG's orders are to first provide emergency medical assistance as well as rations of food and water to the needed areas and second to coordinate with the engineering battalion to effect repairs on the power, transportation and water distribution systems. The CSG has established a command center in the capital city and is developing a plan to provide medical, food, and fresh water to those in need. The command center must first gather essential information on the pre-disaster water distribution system to include: water sources, pipelines, capacities, and minimum requirements at each city. They must also determine the current state of the distribution system.

With the proper planning tool in hand, the command center can quickly access the data files of the government agency responsible for potable water and load the pre-disaster network into the program. With the help of several different agencies the logistics planners are able to modify the network to represent, as closely as possible, the post-quake distribution system. The network describes the cities as nodes and the pipelines, roads, railways, and river routes to the cities as arcs. Each node has assigned to it a number that represents daily water requirements and each arc capacity represents the maximum flow per day through that pipeline. There are 3 water sources and 10 cities on the distribution system, 5 of which are effected by the earthquake.

Once the post-quake data is entered, manually if necessary, the network is used to solve the maximum flow from the 3 sources to each of the cities. The difference between the requirement and the maximum flow to the city can be used to determine quickly a rough estimate of how much water the Army engineers and host nation public works needs to provide to the city. The geographic display is extremely useful here because it quickly shows that two of the cities are on the coast, one is near a river, one city has only one major roadway into it which also has a collapsed bridge, and the other six have accessible roads and minor estuaries nearby. This information is valuable because the planners can determine how much water to deliver, where the source of relief water can come from and what equipment will be needed at each city.

Once the plan is activated to provide the relief supplies, the situation can be monitored to determine if enough water is getting to each city and if not, how to alleviate the problem. The next step is to determine where to repair the network. This can be done simultaneously with the first planning action on a separate personal computer. Having both the abstract and geographic representation is helpful here because new arcs can be added to the abstract representation and analyzed to determine if requirements are being met and then pictured on the geographic map to see if it is feasible to add the arc. It may not be feasible to send water from a particular source to a city because of a mountain range.

One use could be to assign a cost to each arc that represents laying another pipe alongside the existing pipe to improve capacity (for edges not effected by the quake), and the cost to fix or replace the damaged arc. It may be cheaper to lay parallel pipe than to repair and replace a long stretch of underground piping. In any event, as the repairs are made and the situation changes, the network can be easily modified and the data analyzed to ensure that the requirements are being met and it is done as cost effectively as possible. The planning is done on scene, and the network display can be sent back to the central command desk in the United States via an established information network.

B. SCENARIO: COUNTER LOGISTICS

A task force commander is engaged in a lessor regional contingency (LRC) and is trying to eliminate the opposing forces supply of refined fuel. The approach is to destroy existing stocks of refined fuel and eliminate the ability of the orange forces to produce refined fuel. The orange forces have control of a major sector of territory that contains multiple oil wells, a network of pipelines and two refineries. The navy contingent has successfully blockaded the ports to orange forces and the ground troops and air assets have ensured that the flow of supplies into orange territory has been halted. Orange forces are well equipped and still pose a threat to blue forces. It has been determined that if orange forces are deprived of fuel they will lose the means by which to wage war.

Intelligence has been collected on the crude oil distribution network and has been entered into the planning tool. The network consists of source and transshipment nodes (oil fields and associated pumping and relay stations) and arcs (the pipelines, railway, and truck routes that connect the oil fields to the refineries). Each node has certain characteristics associated with it such as capacity and location. The arcs are assigned a cost which represents the relative difficulty and expense to eliminate that arc from the network. The data is analyzed and the minimum cut set that separates flow from the oil wells to the refineries is displayed on both the abstract and geographic map. The two view display quickly shows the task force commander that the solution is indeed a cutset. This is not always obvious on the geographic map, however, by properly arranging the nodes of the abstract display it is readily apparent. The minimum cutset represents the most cost effective way to stop the flow of crude oil to the refineries.

Special operations forces have been sent in to destroy orange force storage facilities and fuel bunkers. Through air strikes, guided munitions from blue armored forces, and special forces operations, the identified arcs have been attacked. Battle Damage Assessments (BDA) indicate that all of the arcs have been destroyed yet the refineries are still operating, albeit at a reduced capacity. The task force intelligence group discovers that two of the arcs were repaired within hours by an on site repair crew and that there must be an underground pipeline from some of the wells to various pumping stations because pumping stations that should have no oil supplied to them are still pumping oil. By conducting a series of "what if" analysis, the analysis team has determined what wells and pumping stations are connected by undiscovered piping. These arcs are added to the network with a cost of infinity since their whereabouts are still unknown. Due to the flexibility of the planning tool, the planning staff is able to easily modify the network with the new data and solve for a new minimum cutset. This process of evaluating the network, identifying cutsets, and then attacking is continued for weeks because the orange force has been adept at repairing and redirecting the flow of oil to the refineries and "what if" analysis has discovered more unidentified arcs in the network. However, due to the blockade and the persistent attack on the network, the supply of repair materials has dwindled and the amount of flow to the refineries has all but ceased. As the flow of oil diminishes, the production of refined fuel is drastically reduced and orange forces are facing the same fate as Rommel in Africa. Constrained by the supply of refined fuel, the orange force's ability to continue aggression is diminished and orange force commanders are advised to negotiate a peace.

The planning tool in this scenario was used to deprive the enemy of a war essential commodity. Counter logistics through network interdiction is possible, however, for it to be successful there has to be a continual process of damage and repair assessment, intelligence gathering, reattack, and reassessment. The model allows for quick and easy modification which makes the assessment and reassessment possible. Because the battlefield situation is very dynamic, for a planning tool to be effective, it too must be dynamic.

C. SCENARIO: INFRASTRUCTURE DEFENSE

A logistics group has set up operations providing Humanitarian Assistance to villages in various locations in a jungle nation as well as direct support to special forces and Civil affairs units assisting local forces with Foreign Internal Defense (FID). Guerrilla forces are well armed and dispersed throughout the nation and plan to disrupt the flow of supplies in order to extort support from the citizens by providing food and health supplies in exchange for votes in upcoming elections. The base camp and Logistics Readiness Center (LRC) has set up on the nearby coast and is well defended by U.S. Marines and resupplied by sea through a small port. The main problem facing the logistics planners is how to best defend the shipments from the base camp en route to the villages. Typically once the shipments reach the villages they are protected by local forces or are distributed safe from guerilla attack.

The various supply routes to the villages have been set up as a network of secondary roadways, villages and transhipment nodes and the port. Source nodes represent the supply center and the demand nodes the villages in need. The arcs are the roadways from the port to the villages and transhipment nodes. Normally, additional arcs representing boat traffic on waterways and helicopter vertical lift would also be represented. However, competing demands for landing craft and lift helicopters have limited the few landing craft to supply the port and helicopters for emergencies. Roadways may pass through a variety of terrain which range from open space to dense jungle. A long stretch of road passing through different types of terrain is separated into as many arcs as the types of terrain, using transshipment nodes. The analysts have devised a system of points that are assigned to the arcs in lieu of capacities. The total points assigned to a given arc is the sum of various attributes of the length of road. The point system consists of three conditional modifiers: type of terrain, the number of roads to a village, and whether a road contains a bridge or tunnel. Wide open terrain is assigned a value of 10 while dense jungle is assigned a value 1. Terrain that is not open but does not provide as much cover as jungle such as farmland or orchards is assigned a value between 1 and 10 and is based on the judgement of the planning staff. The multiple roads to a village modifier is just the number of roads that lead into the village for instance, if there are 5 roads into a village, each arc to that node has a multiple road modifier of 5. Any arc that contains a bridge or tunnel is considered extremely vulnerable and is assigned the lowest possible value, 1, regardless of any other attributes. The total points assigned to each arc is then the sum of the terrain and multiple road modifiers or 1 for having either a road or a tunnel.

The network information is loaded into the planning tool and a minimum cutset that separates the village from the supply center is identified. The minimum cutset represents the set of roads that eliminates all flow from the LRC to the destination(s) that is most vulnerable to guerrilla attack. In planning the route of the next shipment from the LRC to the villages, the analyst assign a path that contains the arc of the cutset with the highest value ensuring that, of the most vulnerable arcs in the network, the least dangerous route is taken. Although the value of this arc may not be assigned the lowest value of all the arcs on the assigned path, the analyst believes it to be the most vulnerable to attack. The value of the cutset arc used is considered the risk factor for the route and is used to determine the number of troops assigned to defend the shipment.

At any given time, intelligence reports from a variety of sources may inform the LRC of guerrilla activity. These reports can be used to modify the risk factors assigned to arcs of the network or may even cause the arc to be deleted if it is determined that all vehicles passing along that arc will be attacked. By redefining the meaning of capacity on the arcs to risk factors, the logistics planners are able to use the planning tool in a unique manner allowing for shipments to be scheduled and transported, or even diverted en route to a route of minimum risk.

The planning tool used in this scenario determines relative risk which allows for the best allocation of defense forces as well as minimizing vulnerability of convoys. This demonstrates that the planning tool can be used to defend ones own infrastructure as well as to find vulnerabilities in the infrastructure of opposing forces.

1. Reverse of Counter Logistics

Another approach to infrastructure defense uses a scenario similar to the counter logistics scenario. Interchange the blue and orange forces so that blue is now on the defensive and needs to ensure that crude oil flows from the oil fields to the refineries to keep its war machine supplied . The network is entered into the planning tool and instead of finding the most vital links to attack, the cutset represents the arcs that require the most defense. In addition to identifying vulnerable arcs, sensitivity analysis can be conducted to determine whether or not diverting flow would be effective as well as how to best effect repairs on the distribution system.

D. SUMMARY OF SCENARIOS

The three scenarios, though simple in nature, illustrate the flexibility in a generic planning tool. In all the scenarios, the maps and data were not required to be on the machines conducting the analysis. The information net allowed for all participants who required information access to it and the dual display provided visual orientation as well as highlighting vulnerabilities. The infrastructure defense scenario also suggests that redefining capacity as a dimension-less risk factor provides as much information as does the flow capacity of goods. The utility of the generic planning tools described here is limited only by the creativity and ability of the user and not by the planning tool.

IV. CONCLUSION

The map based logistics planning tool developed in this thesis is a prototype system that demonstrates a generic planning tool that can be applied to a wide range of situations. The design shifts from procedural based, common to that of the monolithic legacy systems that exist today which are cumbersome and costly to change, to an object oriented approach consisting of multiple components that can be added and deleted without corrupting the utility of the program. The system uses current technologies that allow for the program to be used on and across many computing platforms and is combined with established standards and protocols to allow for information exchange via an information network such as the internet. The advantages to this approach cover a wide range of areas. Because of the capabilities of the programming language, the tool can be used without change on a variety of machines allowing users to share information independent of the type of computing machine and operating system. Inter-agency as well as inter-service lines can be crossed without modification to the programming code eliminating many of the barriers that currently exist when conducting joint and combined operations. The incorporation of established standards and protocols allows the system to be distributed across information networks which, when combined with the systems portability, enables the participants to share information while separated by great distances without the restriction of the type of machine being used at individual sites.

A portable distributed system requires less storage space on the user's machine enabling the system (or some subset of it) to be run on computers with limited resources such as hand held pocket computers. Because the information need only be stored at one location, only one database per capability need be maintained. This reduces the number of database managers required for the entire system. The extensibility of an object oriented component design makes the model robust. Capabilities can easily be incorporated into the model without having to rewrite or recompile the entire program. The model can match capabilities to requirements and provide a useful tool tailored to the situation at hand. This aspect will reduce the cost of maintaining and modifying code since classes used in this tool can be used in others as well. A library of capabilities can be established and accessed by various tools of this design.

The limitation on a system of this design resides in the knowledge of the user and the vision of the developer. By utilizing a library of capabilities, the only limitation is knowing where the capability resides, on the machine being used or on another machine assessable by a computer network, and providing a link to the capability. If the library does not contain a capability then the only constraint is coding the desired capability.

The robustness derived from the extensibility and portability of the map based planning tool creates a savings in resources that can neither be measured nor ignored. The distributed nature allows for near real time flow of information over vast distances which will increase the overall readiness and effectiveness of forces. This prototype lays the ground work for research and development of larger dynamic planning systems whose capability is limited only by the vision of users and developers.

APPENDIX A. GRAPHS, NETWORKS, AND ALGORITHMS

A. DEFINITIONS AND NOTATION

A directed graph G = (N,A) consists of a set N of nodes and a set A of arcs. A directed network is a directed graph whose nodes and/or arcs have assigned numerical values such as cost and capacities [Ref. 8]. An arc is an ordered pair of nodes (i,j) with i and j being elements from the set N, denoted $i,j \in N$ [Ref. 9]. An arc (i,j) in a directed network has as its tail node i, and node j as its head and is said to be emanating from node i and terminating at node j and the arc is said to be incident to nodes i and j. For an arc $(i,j) \in A$, it is said that j is adjacent to i. The arc adjacency list A(i) is the set of arcs emanating from node i. It is assumed that there are no arcs (i,i)[Ref. 8]. A simple path is a subgraph of G consisting of a sequence of adjacent nodes and arcs without repetition of any node or arc. A simple directed path is a path that goes in the direction of the arcs without any repetition of arcs or nodes. A cut is a partition of the node set N into two sets, S and $\overline{S}$. An arc(i,j) is said to be in the cutset if $i \in S$ and $j \in \overline{S}$ or $i \in \overline{S}$ and $j \in S$. An s-t cut is a cut if $s \in S$ and $t \in \overline{S}$. An arc (i,j) is referred to as a forward arc of the s-t cut if $i \in S$ and $j \in \overline{S}$ and an arc (i,j) is referred to as a backward arc of the s-t cut if $i \in \overline{S}$ and $j \in S$. The sum of the capacities of all of the forward arcs in an s-t cut is the capacity of the cut and the s-t cut whose capacity is minimum amongst all s-t cuts is the minimum cut [Ref. 8].

Each arc(i,j) has associated with it a set of parameters that describe its characteristics such as maximum flow capacity and/or cost. Throughout the thesis, capacity was defined as the maximum flow that can pass along a given arc. Cost can be redefined by the user, for example, the cost can represent how much it costs to interdict an arc, or how much it would cost to repair a damaged arc.

To determine the maximum flow through the network, an algorithm is used to send incremental flows down a valid path from the source node *s* to the sink node *t*. In doing this, the network is transformed into a *residual network*. As flow is sent down a path, the amount of flow is subtracted from the arc capacity. The residual network is the "remaining flow" network. There may be many residual networks that lead to the maximum flow solution.

B. ALGORITHMS

The algorithm used in the planning tool to solve for the maximum flow and also identify vulnerable arcs is called the labeling algorithm. The labeling algorithm utilizes the augmenting path algorithm. The two algorithms employ the following theorem:

Theorem (Max-Flow Min-Cut Theorem). *The maximum value of the flow from a source node s to a sink node t in a capacitated network equals the minimum capacity among all s-t cuts* [Ref. 8].

Theorem (Augmenting Path Theorem). A *flow x is a maximum flow if and only if the residual network G(x) contains no augmenting path* [Ref. 8].

Appendix B contains the algorithms mentioned above that are used by the planning tool. The algorithms in appendix B make the following assumptions [Ref. 8]:

1. The network is directed.
2. All capacities are non-negative.
3. The network does not contain a directed path from node s to node t composed

only of infinite capacity arcs.

4. The network does not contain parallel arcs (i.e., two or more arcs with the same tail and head nodes).

If a problem contains multiple min-cutsets, the algorithm will find only one. Although all minimum cutsets have the same capacity, other considerations might lead the planner to prefer one particular cutset over the other minimum cutsets.

APPENDIX B. LABELING ALGORITHM

The algorithm below is the labeling algorithm . The term s is the source node and t is the sink node. Pred(j) is the predecessor of node j, r_{ij} is the residual capacity of arc(i,j), and LIST is an array of labeled nodes.

algorithm labeling
begin
  label node **t**;
  while t is labeled do
  begin
    unlabel all nodes;
    set pred(**j**) := 0 for each **j** $\in$ **N**
    label node **s** and set **LIST** := {**s**};
    while LIST $\neq$ 0 and **t** is unlabeled **do**
    begin
      remove a node **i** from **LIST**;
      for each arc (i,j) in the residual network emanating from node **i do**
      if r_{ij} > 0 and t is unlabeled **then** set pred(**j**) := **i**, label node **j**, and add **j** to **LIST**;
    end;
    if t is unlabeled **then** augment;
    end;
end;

procedure augment
begin
  x := 0;
  while G(x) contains a directed path from node **s** to node **t** do
  begin
    identify an augmenting path **P** from node s to node **t**;
    δ := min{r_{ij}: (i,j)$\in$ **P**};
    augment δ units of flow along **P** and update G(x);
  end;
end;

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